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Neutral Density Behavior from 45-90 km Based on Rayleigh Lidar Observations Above USU

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Abstract

There are over 900 nights of observations taken by the Rayleigh lidar above Utah State University from 1993 to 2004. The data have been reduced to give absolute temperatures and relative densities in the mesosphere, from 45-90 km (Herron, 2004, 2007). From the 11 years of relative density data an 11-year climatology of mesospheric densities above Logan, Utah has been created. From this climatology I have been able to normalize the 11 years of density data to the following models: the MSISe00 empirical model, the CPC (Climate Prediction Center) reanalysis model, the ERA Interim reanalysis model, and the NASA MERRA reanalysis model. The USU relative density climatology is normalized to the models to show how the models behave when they are extended beyond their upper altitude range. The MSIS empirical model has an extensive altitude and goes far beyond 45 km but was chosen due to its extensive use in the scientific community. The reanalysis models CPC and ERA Interim are near their upper bounds around 48 km, while the MERRA reanalysis model extends slightly higher to 65 km. By interpolation I was able to find their values at 45 km and then normalize the data to their values at 45 km where I am able to find their behavior as are propagated through observed data.

Introduction

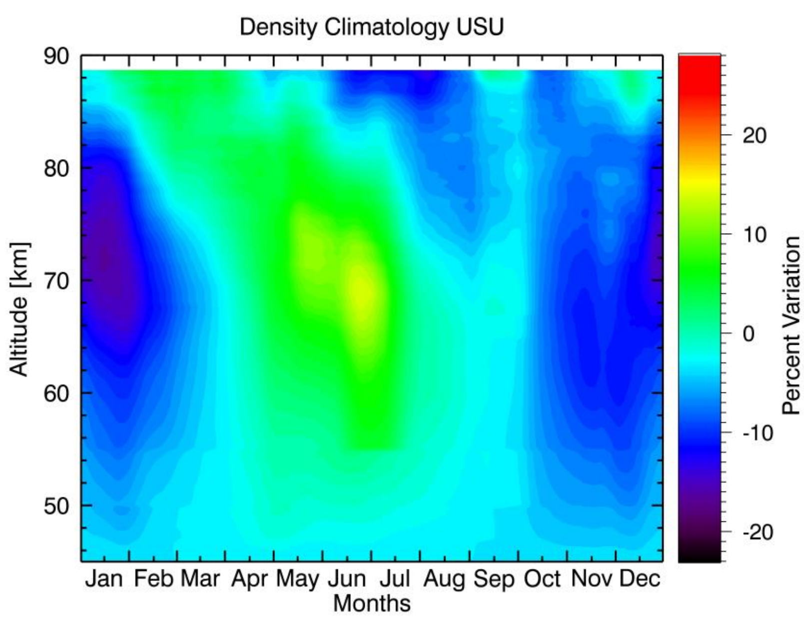

Figure 1; USU relative neutral density climatology normalized to a constant at 45 km.

Atmospheric scientists have attempted to acquire data from Earth's atmosphere for many years. Covering the entire altitude range has proved very difficult. There have been many instruments used to take data but each has its own limitations. Weather balloons have been used to measure densities and temperatures from the ground to 30 km. This allows them to accurately measure from the ground to 30 km. Rockets have also been used to measure the density and temperatures as they go through the atmosphere, but this gives a dataset limited in time and high operational costs. Another possibility is satellite observations. However, their altitude resolution was initially 10 to 15 km, very large compared to the scale over which large atmospheric variations occur. Satellites now can achieve an altitude resolution closer to 3 km, they are able to measure horizontal variations well. Due to their orbits around the Earth they do not measure time evolution well as they orbit the earth rather rapidly. This shows that they are limited in what they can measure but are however complimentary to lidar measurements. Radar, resonance lidar, and airglow photometers have also been used to measure densities, temperatures, and winds in the atmosphere but, they are limited in altitude range. The lowest altitude for these instruments is typically around 80 km. These observational techniques leave a large hole between 30 and 80 km, which poses a problem for atmospheric scientists and aeronomers. Since 1978, ground-based, Rayleigh-scatter lidars have come along to fill the gap. They have been used to determine temperatures and relative densities in the 35-90 km altitude range.

Due to the lack of measurements in the altitude range 35-90 km, we are at an advantage at USU because we have such a large Rayleigh scatter lidar data set covering the altitude range 45-90 km. While temperatures have been looked at extensively, the relative densities have barely been examined. To explore the densities in the 45-90 km region, the mesosphere, we would like to attach an absolute scale to these relative densities. To do that, we turn to the models that cover this altitude region. The MSISe00 model is an empirical model that almost everyone refers to, making it an important reference. The CPC is the oldest of the reanalysis models being considered here. It goes up to 1 hPa, which is just above 45 km. The ERA Interim model is a much more recent reanalysis model. It too goes up to 1 hPa. The MERRA model, the other recent model, goes slightly higher, up to 65 km. While the model calculations go just above the 45 km of the lidar data, they have very little data to go on. However, they are about all there is to use to normalize the lidar data, which begins at 45 km.

Project goals

This project is to build on research that I started with a mini grant from the College of Science, over a year ago, on mesospheric neutral densities. This is to be done by extending density normalizations of our lidar data at 45 km to two more models that are much more recent. The goal is to determine, or at least learn about, seasonal variations of density in the mesosphere as a function of altitude. The goal is also to determine what more might have to be learned in future observations to complete the job. The first part of the research was a preparatory phase. It involved working with complex scientific algorithms (MSIS) and large scientific databases (the three reanalysis models): ERA Interim, MERRA, and CPC. This gave four different sets of values to use to normalize the density observations at 45 km. The second part was to determine the seasonal variations as a function of altitude and determine what was common and what was different among the four analyses. The common parts would tell us much about mesospheric density variations. The different behaviors would identify what needed to be looked at in future observations and experiments.

Method and results

The relative densities from each night of data from the Rayleigh lidar were derived from the 11-year data set by Herron (2007). The averaged profiles were scaled to a constant at 45 km. For every night of the year, I averaged the nightly averages from all the nights within a window 31 days wide centered on that day of the year and 11 years deep. Within the limits of a constant density at 45 km, these profiles do show considerable seasonal variation at each altitude between 45 and 90 km, Figure 1.

The idea behind this project is to learn more about these seasonal density variations. The idea is to include the extra information provided by the models. To do this, each of the 900 or so observed density profiles is scaled to the model density at 45 km for the same night. Then a composite climatology is produced by successively averaging over the same 31 day by 11 year window. Because the density at 45 km will vary during the year for many reasons, including insolation and weather systems, the expectation is that each composite climatology will show a greater variation than the initial one based on a constant density at 45 km.

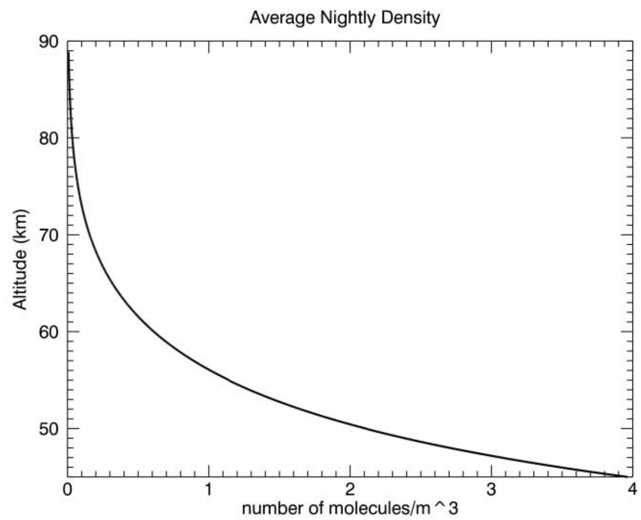

Figure 2, Average density Profile

Obtaining the MSISe00 densities was relatively straight forward because, given the correct inputs, the model densities are calculated as a function of altitude by a complex algorithm. However, the algorithm had to be acquired from a MSIS team member at NRL. The reanalysis models have profiles of pressure and temperature as a function of geopotential altitude on a global grid for every day in a window that includes our observations. These are huge databases, which are of course in different formats. Methods were developed to import and select the proper data. Temperature and pressure values were then given as a function of geopotential height. These were converted to altitude above the geoid (mean sea level) and interpolated to find the temperatures and pressures at 45 km. The ideal gas law, $p = nkT$, was used to find the number densities, where p is the pressure, n is the number density, k is Boltzmann's constant, and T is temperature.

For the 900 nights of good densities, a daily 31 day by 11 year average was constructed, giving a composite annual, density climatology. In Figure 2 we see that the density profiles change by approximately 3 orders of magnitude from 45-90 km , it was important to find a way to display relatively small (approximately 30% maximum at any altitude), but significant density variations at any altitude. This was done by plotting the derived densities at each altitude as a percent variation from a mean density profile. A number of different mean profiles could have been calculated and chosen. The one selected was the mean of all the profiles from the four composite models. It was calculated by taking the average density of each model and then averaging those averages together thus creating an average profile of all of the models. I then calculated my percent variation from of each model from this average profile. It is shown in Figure 2. From there we have a starting point for comparing the effects of each of the four normalizations applied to our relative density profiles. Thus these four climatologies, derived in this way, reflect our observed relative densities, which have been normalized to the model densities at 45 km.

Conclusions

The observed relative densities normalized to a constant at 45 km show the existence of seasonal structures. These structures are amplified in various ways when normalized to the 45 km densities in the four models, Figures 3-6 and Figures 7-10.

What was found can be broken down into what was learned about the four models and what was learned by combining the observed densities and the 45 km densities, Figure 11.

Comparisons among the Four Models:

- The four models differ significantly at 45 km, as one might expect for the reanalysis models because 45 km is very near the top of their altitude range.
- CPC and MERRA show relatively similar variations at 45 km, dominated by an annual variation.
- ERA Interim shows lower densities at 45 km than the other models.
- ERA Interim also shows considerably more structure at 45 km, leading to relative density maxima in April, July, and December.
- MSISe00 also has a relative maximum in March.

Seasonal Variations in the Lidar Densities and the Four Models:

- Both the largest relative densities (June/July) and smallest relative densities (January) occur at approximately 70 km.
- At lower altitudes, in all models except ERA Interim, the maximum relative density shifts later to early July and the smallest relative density shifts earlier to December.
- Above about 75 km the relative density maximum shifts earlier, occurring in February and March at 90 km.
- In addition, considerable structure appears starting in March above 85 km, with a relative density maximum in September.
- The ERA Interim model also gives rise to a relative maximum in December at all altitudes.
- A sharp density fall off at all altitudes occurs at the beginning of October.

Given both the lidar data set and the models, several additional studies should be carried out in the near future.

- One study would be a detailed comparison between the lidar and MSISe00 densities between 45 and 90 km. This would examine if the two have the same seasonal variation.
- Another study would be a similar comparison between the lidar and MERRA densities between 45 and ~65 km.
- Now that the model data are available, a different study would be to compare temperatures day-by-day at 45 km. This would examine whether or not the variability seen in the lidar temperatures originates from meteorological processes in the troposphere.
- The most important thing to do next observationally is to extend the lidar observations down to about 15 km to obtain a much better density normalization with balloons and/or reanalysis models. This involves observing Raman scatter in addition to Rayleigh scatter. This would put an absolute density scale on the whole density profile from 15 to 120 km.

- After a number of such extended Rayleigh and Raman observations it would be possible to put strong constraints on these models and to distinguish between them.

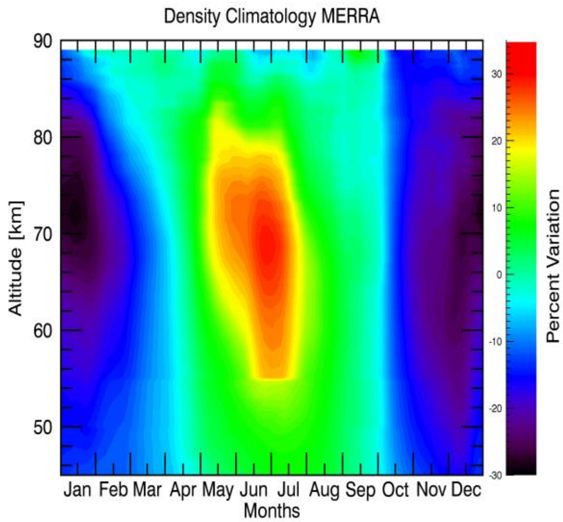

Figure 3, MERRA Density Climatology

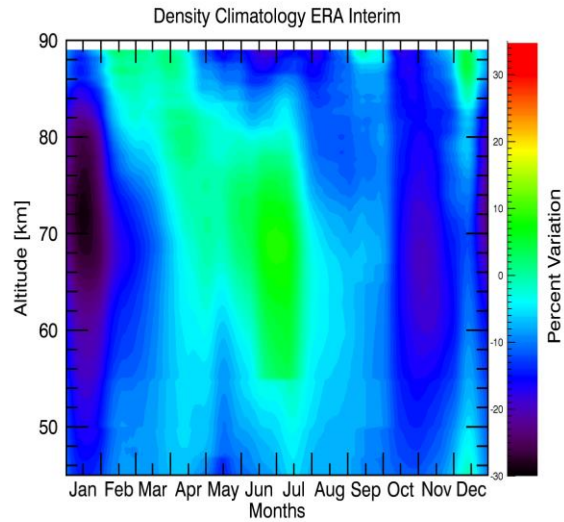

Figure 4, ERA Interim Density Climatology

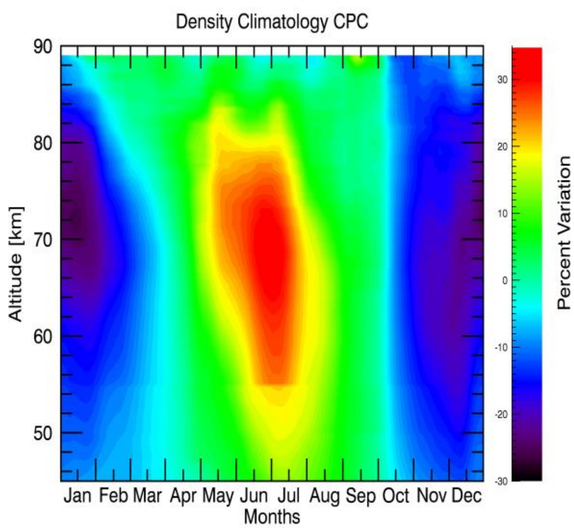

Figure 5, CPC Density Climatology

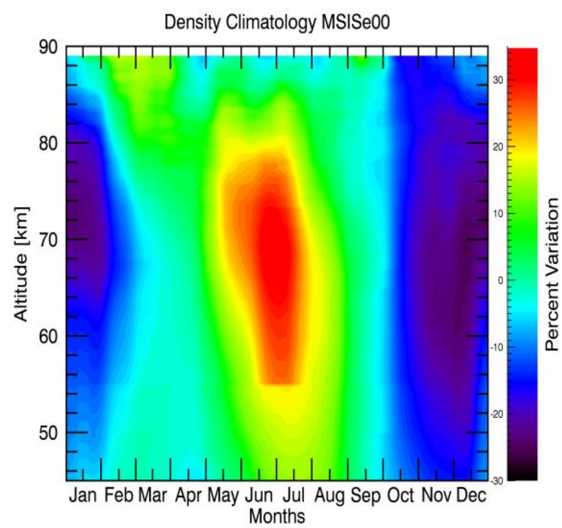

Figure 6, MSIS Density Climatology

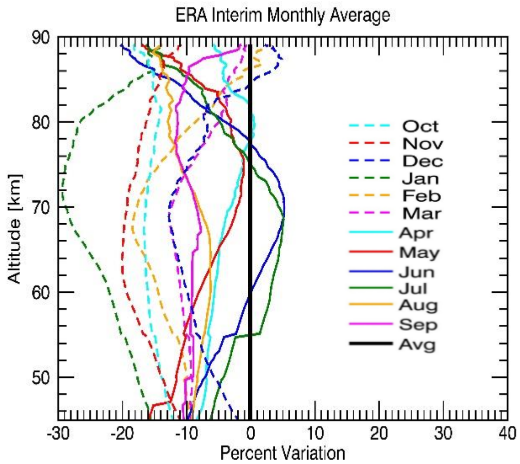

Figure 7, ERA interim monthly average

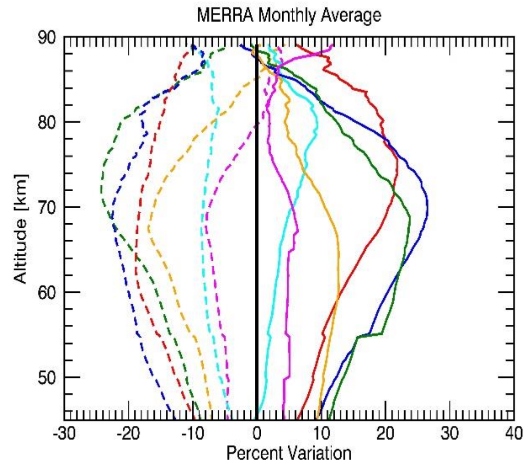

Figure 8, MERRA monthly average

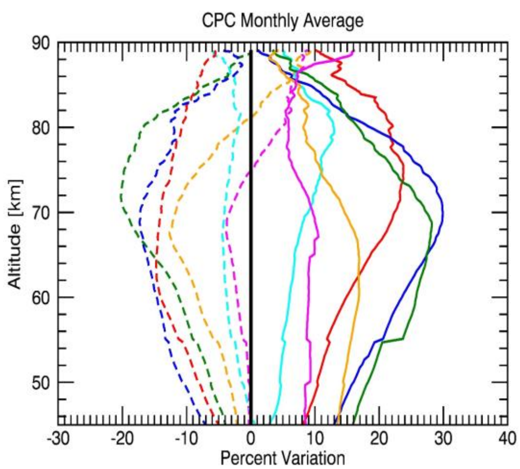

Figure 9, CPC monthly average

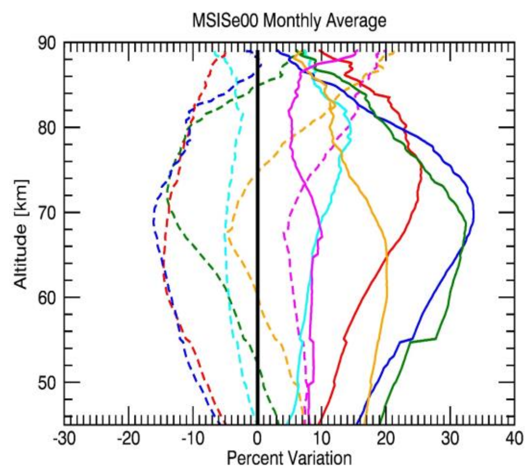

Figure 10, MSISe00 monthly average

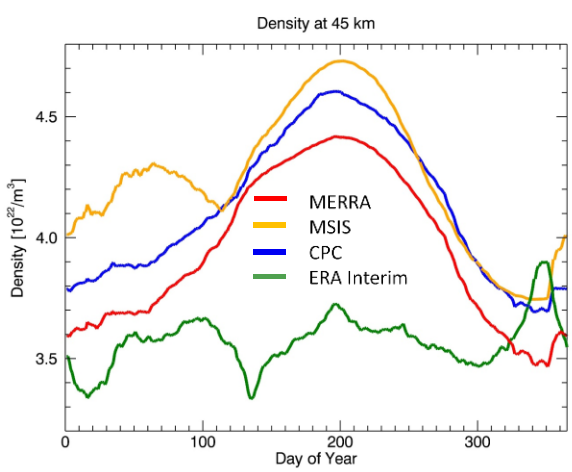

Figure 11, 45 km snapshot

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